INVESTIGATION OF VERTICAL PROFILES OF MEAN TEMPERATURE, WIND AND HUMIDITY

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THESIS

INVESTIGATION OF VERTICAL PROFILES
OF MEAN TEMPERATURE, WIND AND
HUMIDITY

by

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March 1975

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to previous experimental results obtained in defining the meteorological parameters of friction velocity, roughness length, drag coefficient and the Richardson number. The temperature structure parameters computed from the profiles were provided to Lund (1975) for comparison with direct measurements.

In general, favorable results were obtained in the parameter comparisons which provided additional support to the suitability of shipboard profile measurements defining the marine surface layer. However, some evidence exists in roughness lengths and drag coefficient values to indicate that the ship's structure may be a factor influencing results.

Investigation of Vertical Profiles
of Mean Temperature, Wind and
Humidity

by

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Lieutenant, United States Navy
B.S., Miami University, 1966

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY

from the

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March 1975

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Shipboard measurements of the vertical profiles of mean humidity, temperature and wind speeds over the ocean have been investigated to verify their suitability to accepted turbulence similarity theory. In addition, the profiles have been used to obtain estimates of the temperature structure parameter. One hundred eighty-two profiles observed over a seven month period in 1974 aboard the R/V Acania in Monterey Bay have been compared to previous experimental results obtained in defining the meteorological parameters of friction velocity, roughness length, drag coefficient and the Richardson number. The temperature structure parameters computed from the profiles were provided to Lund (1975) for comparison with direct measurements.

In general, favorable results were obtained in the parameter comparisons which provided additional support to the suitability of shipboard profile measurements defining the marine surface layer. However, some evidence exists in roughness lengths and drag coefficient values to indicate that the ship's structure may be a factor influencing results.

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Finally, to my wife, who served as my inspiration throughout the endeavor, my deep and continued devotion.

I. INTRODUCTION

The air-sea interface region has many physical properties yet to be fully understood. Only in the past decade has there been a concerted effort to make measurements in the planetary boundary layer over the ocean and to examine existing laws describing it. The Navy is actively engaged in marine atmospheric boundary layer research for many reasons. One of which is to accurately access the environmental influence on optical wave propagation over the ocean. Experimental evidence suggests that certain near surface atmospheric parameters can give reasonable results in specifying the optical conditions for the first tens of meters above the sea. In this area, problems involving applied theory, shipboard instrumentation and data processing exist.

A primary purpose of this work is to evaluate, for the marine boundary layer, expressions which have been formulated on the basis of previous experiments.

Data examined in the study were measured from the Naval Postgraduate School research ship, the R/V Acania shown in figure 1. Beginning with accepted basic surface layer theory and advancing to turbulence similarity theory, observed data is analyzed in part for its practicability in defining optical wave properties in an ocean environment.

The suitability of the R/V Acania as a platform for ocean micrometeorological measurements was previously examined in

Research Vessel Acania

Figure 1

detail by Cavanaugh (1974) and Welsh (1974) and verification of their work is a secondary objective.

Examined in this study are ten minute time averaged values of wind, temperature and relative humidity measured at generally four levels. The observations were made during the months of February, March, August and September 1974 while the R/V Acania was at anchor approximately two miles offshore in Monterey Bay. Coincident with these measurements were measurements to obtain spectra of the wind and temperature flunctuations and also measurements of optical propagation characteristics. The agreement of the profile data with boundary layer theory predictions and results of others will be examined to determine the validity of the shipboard measurements.

The boundary layer parameters examined are the roughness length (z_o), friction velocity (u_*), drag coefficient (C_D), Richardson number (Ri), and the temperature structure parameter (C_T^2). Examinations of some of these parameters are accomplished by applying the data to different calculation methods.

The structure parameter is calculated from an indirect method based on similarity turbulence theory as proposed by Wyngaard, Izumi, and Collins (1971). The results were used in comparisons by Lund (1975), who analyzed direct measurements of this parameter for the same data periods.

II. THEORETICAL BACKGROUND

A. GENERAL

Investigations of temperature and wind fluctuations in the surface layer provide a basis for defining the stratum dynamics by turbulence similarity theory. Measurements of mean wind ($\overline{u}$), mean temperature ($\overline{T}$) and mean relative humidity ($\overline{q}$) over a time scale greater than that of the fluctuating motion are used to estimate the vertical fluxes of momentum and heat due to the fluctuations, This can be accomplished because profiles of the aforementioned parameters are maintained by the momentum and heat fluxes. Turbulence similarity theory which is often referred to as the Monin-Obukhov theory relates the profiles to the fluctuation properties. Statistical analysis is used to arrive at empirical expressions which are accepted and are consistent. Dimensional analysis was used in the formulation of all expressions.

The empirical relationships relating gradients of wind, temperature, and humidity to the two fluxes are

$$\frac{\partial \overline{u}}{\partial z} = \frac{u_*}{kz} \phi_m \left(\frac{z}{L}\right) \tag{1}$$

$$\frac{\partial \overline{T}}{\partial z} = \frac{T_*}{kz} \phi_H \left(\frac{z}{L}\right) \tag{2}$$

$$\frac{\partial \overline{q}}{\partial z} = \frac{q_*}{kz} \phi_E \left(\frac{z}{L}\right) \tag{3}$$

Starred quantities of wind (u_*) and temperature (T_*) include the vertical flux parameters as indicated in the following expressions.

$$u_* = (-\overline{uw})^{\frac{1}{2}} \tag{4}$$

$$T_* = -\frac{\overline{w\theta}}{u_*} \tag{5}$$

$$q_* = -\frac{\overline{wq}}{u_*} \tag{6}$$

B. PROFILES IDENTIFYING SURFACE LAYER CHARACTERISTICS

Logarithmic plots of mean wind profiles can be used to define certain surface layer properties such as roughness length (z_o), friction velocity (u_*) and drag coefficient (C_D). The latter is normally calculated for a ten meter height.

Integrating equation (1) and assuming neutral or near neutral stability conditions, where $\phi_m(z/L) = 1$, yields the equation

$$\overline{u}(z) = \frac{u_*}{k} \ln \frac{z}{z_o} \tag{7}$$

The wind speed at the surface, $\overline{u}(z_o)$ is assumed to be zero for reasons of profile analysis. However, that may not be the case if the surface is also in motion, as is the case over the open ocean. Wind measurements taken at several levels and plotted as a logarithmic z profile yield an intercept of z_o and a slope of k/u_*. Figure 2 is a representation of theoretical versus actual wind profiles in the marine surface boundary layer.

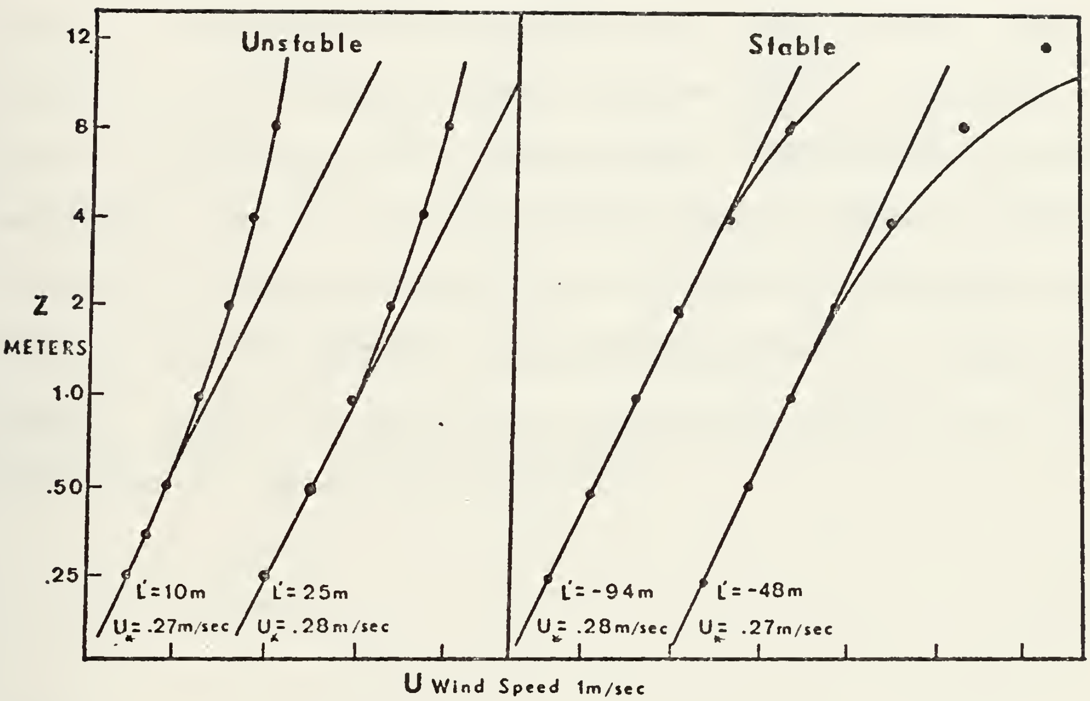

Unstable
Stable
12
8
4
Z 2
METERS
1.0
.50
.25
L'=10m
U*= .27m/sec
L'= 25m
U*= .28m/sec
L'= -94m
U*= .28m/sec
L'= -48m
U*= .27m/sec
U Wind Speed 1m/sec

Figure 2

The drag coefficient is defined as the ratio of the squared friction velocity to the squared mean wind speed at a specific height.

$$C_D = \frac{u_*^2}{\bar{u}_z^2} \tag{8}$$

C. DESCRIPTIONS OF STABILITY INFLUENCE ON THE SURFACE LAYER

The functions ϕ_m, ϕ_H, ϕ_E are used to account for the stability influence in equations (1), (2), and (3). The stability of the surface layer regime plays an important role in determining flux intensities. Monin-Obukhov theory determines the level where mechanical and thermal production of kinetic energy are equal to a dimensionable length (L). The ratio of the height of the measurement (z) to the Monin-Obukhov length (L) serves as a stability index, z/L. The Monin-Obukhov length is defined as

$$L = \frac{T_v \; u_*^2}{qk \; T_{*v}} \tag{9}$$

where

$$T_{*v} = T_* + .61 \; q_* \; \overline{T} \tag{10}$$

In unstable conditions the stability parameter (z/L) is approximately equal to the Richardson number (Ri) which is often used as the stability parameter. The following relationships between the stability parameter and the Richardson number have been proposed by Dyer and Hicks (1970) (unstable) and Webb (1970) (stable).

$$\frac{z}{L} = \frac{Ri}{1 - \alpha\, Ri} \qquad \text{(stable)} \qquad (11)$$

$$\frac{z}{L} = Ri \qquad \text{(unstable)} \qquad (12)$$

α is an empirically derived constant equal to .5.

D. INDIRECT CALCULATION OF THE TEMPERATURE STRUCTURE PARAMETER

The temperature structure parameter (C_T^2) is the most important variable in determining the optical propagation characteristics of the atmosphere. One means for calculating C_T^2 is by employing turbulence similarity theory. Since atmospheric refractive index fluctuations are not included in these calculations, the method indicated is an indirect estimation of atmospheric optical properties. In similarity theory estimates of the dissipation of turbulent kinetic energy (ε) and dissipation of temperature variance (ε_θ) provide the link between direct methods such as proposed by Corrsin (1951), equation 13, and the conveniently relatable vertical fluctuations of wind and temperature in the surface layer.

$$\phi_T(k_1) = \beta_1 \varepsilon\varepsilon_\theta{}^{-1/3}\, k^{-5/3} \qquad (13)$$

Research by Wyngaard, Izumi and Collins (1971) has resulted in nondimensionalized expressions relating atmospheric stability to the structure parameter. Dimensional analysis of the height (z), the friction velocity (u_*), the mean potential temperature gradient ($\frac{\partial\overline{\theta}}{\partial z}$), ε, ε_θ and C_T^2 produce

functional expressions dependent only on the Richardson number. Similarity principals are elucidated by using the nondimensional stability parameter Richardson number defined as equation 14 for indirectly obtaining a comparable structure parameter to identify the optic properties existing in the surface layer.

$$Ri = \frac{\frac{g}{\overline{T}} \frac{\partial \overline{\theta}}{\partial z}}{\left(\frac{\partial \overline{u}}{\partial z}\right)^2} \tag{14}$$

Equations including the Richardson number functions (f_1, f_2, f_3) are

$$\frac{z\varepsilon}{u_*^3} = f_1\ (Ri) \tag{15}$$

$$\frac{\varepsilon_\theta}{z u_* \left(\frac{\partial \overline{\theta}}{\partial z}\right)^2} = f_2\ (Ri) \tag{16}$$

$$\frac{C_T^2}{z^{4/3} \left(\frac{\partial \overline{\theta}}{\partial z}\right)^2} = \frac{3.2\ f_2}{f_1^{1/2}} = f_3\ (Ri) \tag{17}$$

The latter expression relates the temperature structure parameter and stability parameter and allows for an empirical determination of the f_3 function at varying conditions of stability. If the function f_3 is defined, the temperature structure parameter can be readily calculated from more easily measured parameters, $\frac{\partial \overline{\theta}}{\partial z}$ and Ri.

III. EXPERIMENTAL OBSERVATIONS

A. DATA COLLECTION

The Naval Postgraduate School R/V Acania was the observational platform. The ship was anchored in Monterey Bay at a location approximated in figure 3. This location facilitated complimentary and simultaneous optical experiments from two shore stations, Hopkins Marine Station and the Holiday Inn. Normally, observational periods were three days in duration beginning with a one day equipment calibration and set up, continuing with a one day on station systems test and finishing with one day of data collection. Data collection was mainly during evening hours. The entire operation required considerable inter-departmental coordination between the meteorology and physics departments.

Data was collected and analyzed for the dates and time shown in table 1. These observations represent over ninety percent of all the mean profiles obtained in Monterey Bay during the period from 25 February to 20 September 1974.

Figure 4 shows the general instrument configuration used during the experiments. Variations in the arrangement occurred primarily because of individual component failures.

B. EQUIPMENT

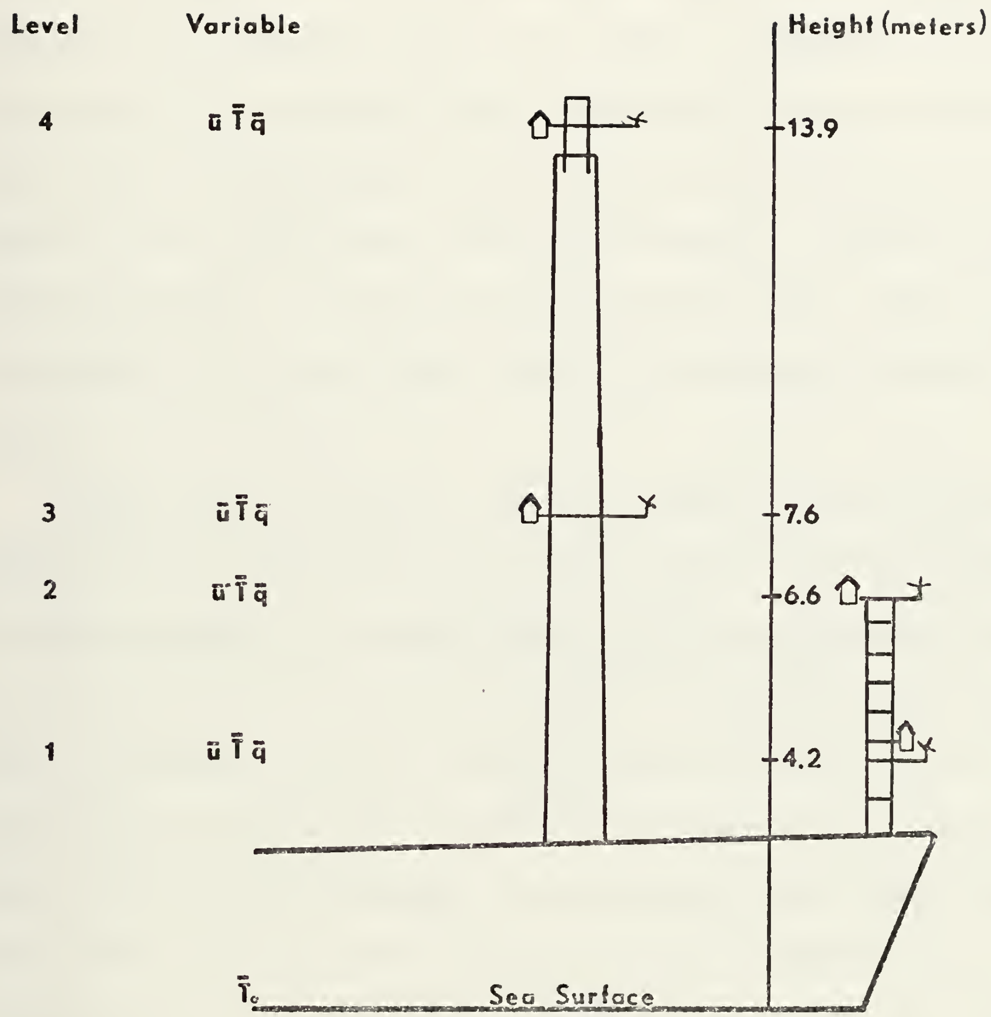
The mean wind measurements were made with a Thornthwaite Associates cup anemometer wind profile register system,


N
MONTEREY BAY
HOPKINS MARINE
SHIP
HOLIDAY INN
C.G. PIER
MONTEREY
SCALE: MILES
0
.5

Figure 3

DATE	TIME	NUMBER OF LEVELS	NUMBER OF PROFILES
26 February	1113-2225	4	23
27 February	1643-2150	4	25
14 March	1703-2138	2	20
27 March	1823-2142	3	17
28 March	1824-2150	4	14
13 August	1630-2200	4	26
18 September	1617-2202	4	24
19 September	1724-2353	4	25
20 September	0004-0644	4	8

Table I

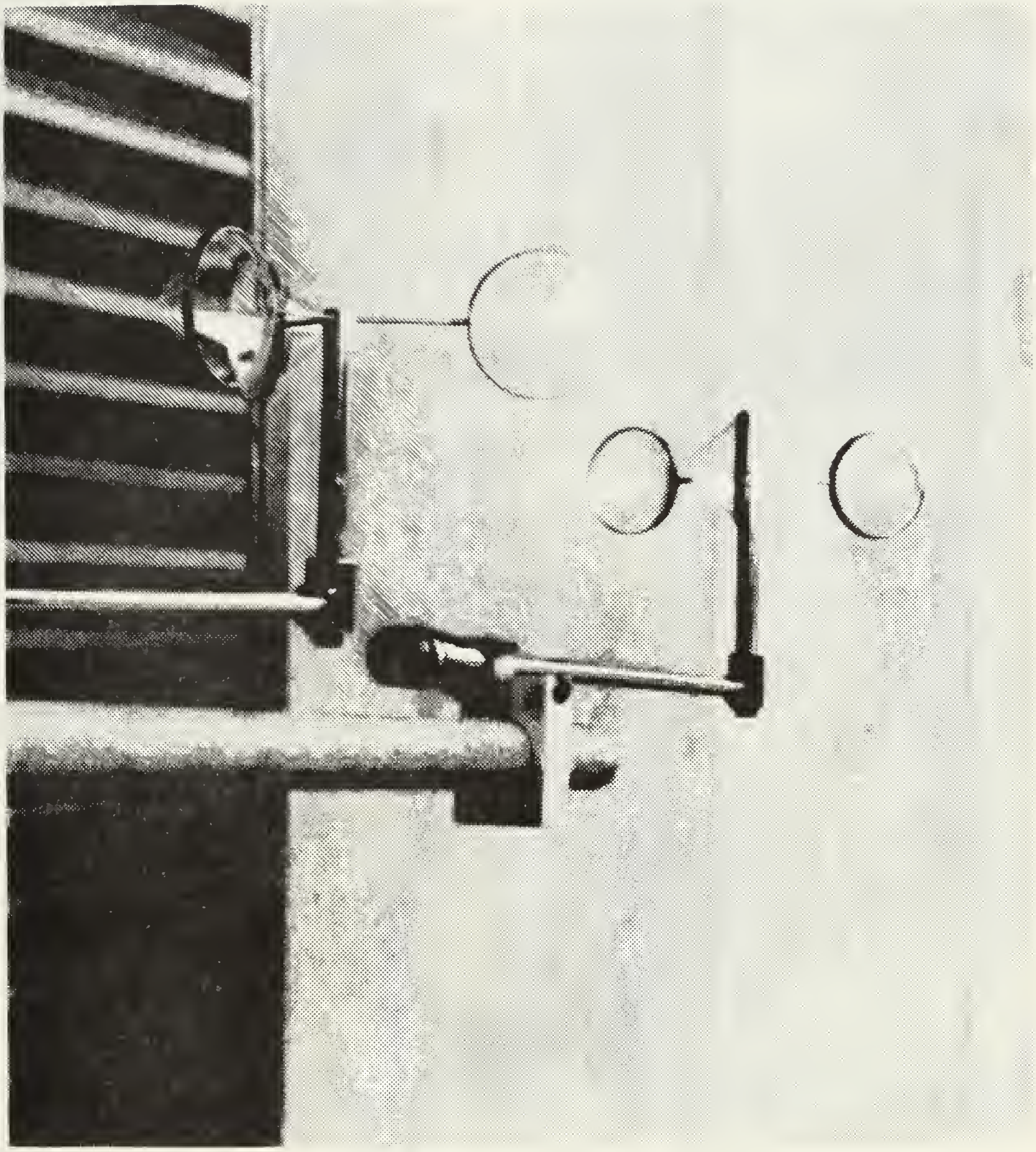


Level
Variable
Height (meters)
4
$\bar{u}\,\bar{T}\,\bar{q}$
13.9
3
$\bar{u}\,\bar{T}\,\bar{q}$
7.6
2
$\bar{u}\,\bar{T}\,\bar{q}$
6.6
1
$\bar{u}\,\bar{T}\,\bar{q}$
4.2
$\bar{T}_o$
Sea Surface

Figure 4

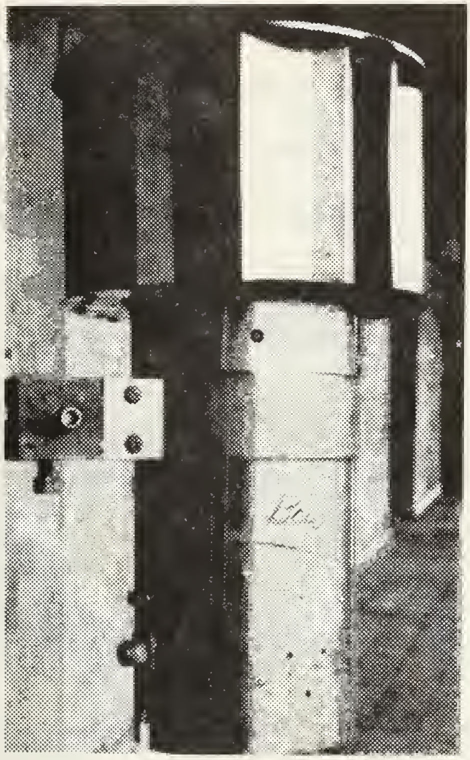
model number 104. In operation the shaft of a three cup anemometer unit serves as the shutter between a light source and a photocell for each revolution. The cups are plastic cones reinforced with aluminum frames. They are attached to the rotating shaft by stainless steel tubing spaced at 120 degree intervals about the shaft as shown in figure 5. The three cup assembly sets along with the other sensors were positioned at four levels on the bow with electrical leads to the after deck house laboratory. The sets have the characteristics of low starting speeds with a small amount of internal friction which aids in checking inertial overshoot.

Temperature sensitive quartz crystal probes, (Hewlett Packard model HP-2850) were used to measure mean temperatures at each level. RF signals from the crystal probes and from a reference oscillator were mixed in the HP-2801A readout unit to produce a beat frequency whose signature can be analyzed to within 0.001 degrees centigrade per hertz. Each sensor simultaneously received pre-experiment calibration against a platinum resistence wire thermometer in a temperature controlled circulating water bath over the expected temperature range. The accuracy in achieving a .005 degree centigrade correction factor was a constant for each probe. A 3.7 meter flexible coaxial cable is permanently attached to the sensor head and the mast mounted probes are housed in an aspirated shelter as depicted in figure 6. Temperature values were automatically recorded on a printer

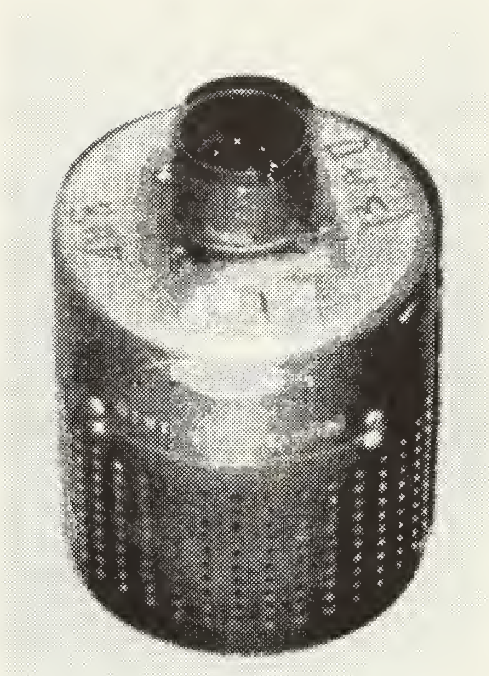


C.W. Thornthwaite Anemometer Cups

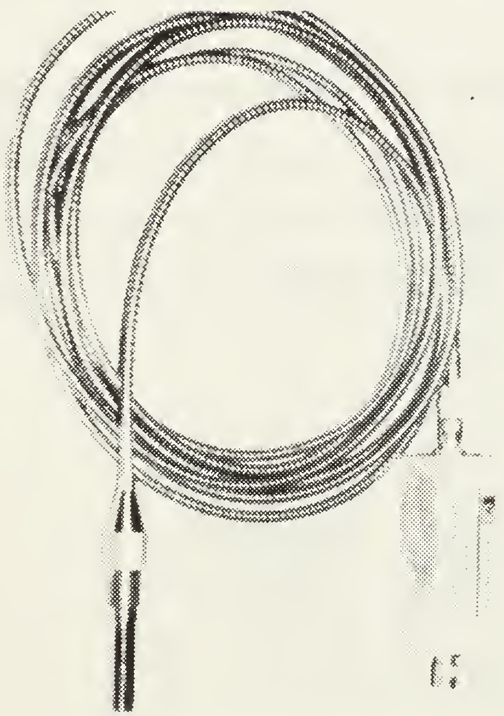
Figure 5



C.C. Breidert Company
Air-X-Houster Type 6L



Dunmore-type Lithium
Chloride Sensor



Quartz Thermometer Probe

Figure 6

tape. The Hygrodynamics Digital I hygrometer indicator and the Dunmore-type lithium chloride sensor were used to measure the relative humidity. The Dunmore-type lithium chloride sensor is illustrated in figure 6. The equipment operates on the basis of resistence change within an electrolytic solution generating a reference voltage variance which is proportional to the relative humidity change. Automatic temperature compensation in the instruments meet the following specifications for relative humidity.

$\pm$ 3% relative humidity below 90%

$\pm$ 4% relative humidity above 90%

Calibration of the sensors was accomplished by comparative methods using saturated salt solutions in an enclosed chamber.

Relative humidity was observed and recorded similar to that of temperature, as a printed output. A more detailed description of the devices, their calibration and deployment can be obtained from Cavanaugh (1974).

IV. ANALYTICAL DATA PROCESSING

A. DATA EDITING

During the experiment, mean wind measurements over ten minute intervals were recorded in a log book. The recordings were the number of cup revolutions for the interval as recorded by electronic counters. Temperature readings were printed on a paper tape from a monitoring digital readout at approximately one second intervals. Initially relative humidity measurements were recorded the same as the temperatures. However, due to a printer malfunction, these readings were recorded by hand in log book after the 28 March cruise. All information was later coded and key punched on computer cards for further analyses.

Preliminary screening processes were performed on computer listings. The data were examined for gross errors or inconsistencies. Very few deletions were necessary at this phase. Next, individual mean wind and mean temperature measurements were plotted to give logarithmic graphical profiles for each time period. The computer program devised for this operation also performed a least squares fit of the data.

In addition, mean wind profiles for certain periods were closely examined for any biases which might be caused by the ships' hull or superstructure. Approximately ten per cent of all the measurements was discarded either because

of incongruous profiles or uncomplementary data times. Rejected profiles were mainly those of wind. They occurred principally when winds were very light.

Temperature profiles were rejected when one or more of the automatically recorded readings appeared to be spurious. This was not discovered during the initial data inspection.

B. DATA RECORDING ADJUSTMENTS

Since the data was obtained over a seven month period, significant alterations in data recording took place due to equipment failure or experiment deviations. Mean wind readings were obtained at four levels for all the periods except when the number of levels were two and three for March 14 and 27 respectively. In August, the order in which the mean wind levels were labeled changed from previous cruises. This data variation was compensated for by analyzing the measurements on a cruise to cruise basis with simple computer program modifications. There were no major problems encountered in programmed analysis of the temperature data. When the indicated relative humidity was missing, adjustments were made by taking an average between the two adjacent available measurements.

C. PROGRAMMING CONSIDERATIONS

Cup anemometer readings were recorded in revolutions per time period. The relationship between revolutions to speeds in nonlinear. It changes with wind speed. A computer subroutine was devised to convert the number of cup rotations

into wind speed. The conversion accuracy for wind speeds decreases with decreasing revolutions.

An IBM System/360 source library program called LSQPL2, Least Squares Polynomial Fitting, was an integral part of the data analyses. LSQPS2 not only served to give linear functions for data profiles, but also was used as a means for approximating roughness length (z_o) values. Once the least squares linear profiles had been calculated, profile values were estimated for levels one meter either side of the observation levels. This was done for the purpose of defining gradients used in computations of the Richardson numbers.

The basis for describing stability in discerning optical propagation conditions is the Richardson number. In testing for the feasibility of applying identical relationships over the ocean, Richardson numbers were determined from the Monterey data utilizing procedures similar to those set forth by Wyngaard et al. (1971). Mean profiles of temperature and wind were obtained by an analytical least squares fit of ten minute mean observations at their respective instrument heights. This provided the wind and potential temperature gradients necessary to compute a Richardson number at each of the four instrument levels. Equation 18 is the approximation for the mean wind speed gradient between two levels used in equation 14.

$$\left.\frac{\partial \bar{u}}{\partial z}\right|_{z_3} \doteq \frac{\Delta \bar{u}}{\Delta z} = \frac{\bar{u}(z_2) - \bar{u}(z_1)}{z_3 \ln z_2/z_1} \tag{18}$$

z_3 represents the geometric mean height, $(z_1 \cdot z_2)^{\frac{1}{2}}$. A similar expression was used to compute temperature gradient, $\frac{\partial \bar{\theta}}{\partial z}$.

V. DATA ANALYZATION AND COMPARISONS

A. FRICTION VELOCITY AND ROUGHNESS LENGTH RESULTS

Important parameters describing the marine boundary layer are the friction velocity (u_*) and roughness length (z_o). The friction velocity is a measure of the momentum transfer described by equation 4 and the roughness length is a boundary parameter defined as the height where the logarithmic profile becomes a valid specification. These parameters were calculated from the data by two methods. One method utilized all profile levels, the other utilized only the wind speed at one level and the air water temperature difference. This was done to determine what difference would occur if the surface layer properties were obtained using data from one level instead of from a four level profile.

The first method was based on a least squares fit of a stability corrected four level profile. The stability influence was determined at each level from the Richardson number. The following Richardson number categories were used in the corrections.

$-0.05 < Ri < .001$	neutral
$Ri > .001$	stable
$Ri < -.05$	unstable

Stability relationships in equation 11 and 12 were used to obtain the stability length (z/L) which was then used to obtain the correction to the empirical expression for mean wind.

The plot of the mean wind versus the logarithm of height with the stability correction should theoretically give a straight line with a slope of k/u_* and an intercept of z_o. Equation 19 was used to incorporate the stability influence into the profile

$$\ln z - \psi_m(\frac{z}{L}) = \frac{k}{u_*}\,\bar{u}(z) + \ln z_o \qquad (19)$$

The function $\psi(\frac{z}{L})$ was defined as follows from Paulson (1970)

$$\psi(\frac{z}{L}) = 2\ln\left[\frac{(1+x)}{2}\right] + \ln\left[\frac{(1+x)^2}{2}\right] - 2\tan^{-1} x + \frac{\pi}{2} \qquad (20)$$

$$x = (1 - 16(\frac{z}{L}))^{\frac{1}{4}} \qquad \text{unstable} \qquad (21)$$

$$\psi(\frac{z}{L}) = -4.7\,\frac{z}{L} \qquad \text{stable} \qquad (22)$$

A least squares fit was applied to the corrected profile to obtain the best estimate of the slope and intercept thus yielding the profile values for friction velocity and roughness length.

The second method was to use a calculation suggested by Cardone (1969). He formulated an iterative procedure to find friction velocity and roughness length given a mean wind, an air-sea temperature difference and the instrument heights. By utilizing wind and temperature gradient expressions combined with equations similar to 9, an iterative algorithm was developed, which gives stability length convergence to a desired accuracy. The friction velocity was obtained using the stability criterion. The roughness length was then calculated from the friction velocity and

the following expression from Cardone.

$$z_o = \frac{C_1}{u_*} + C_2 u_* - C_3 \tag{23}$$

The constants contained in equation 23 were derived so that the ten meter drag coefficient (C_{10}) would be a minimum when the mean wind speed was approximately six meters per second under neutral conditions.

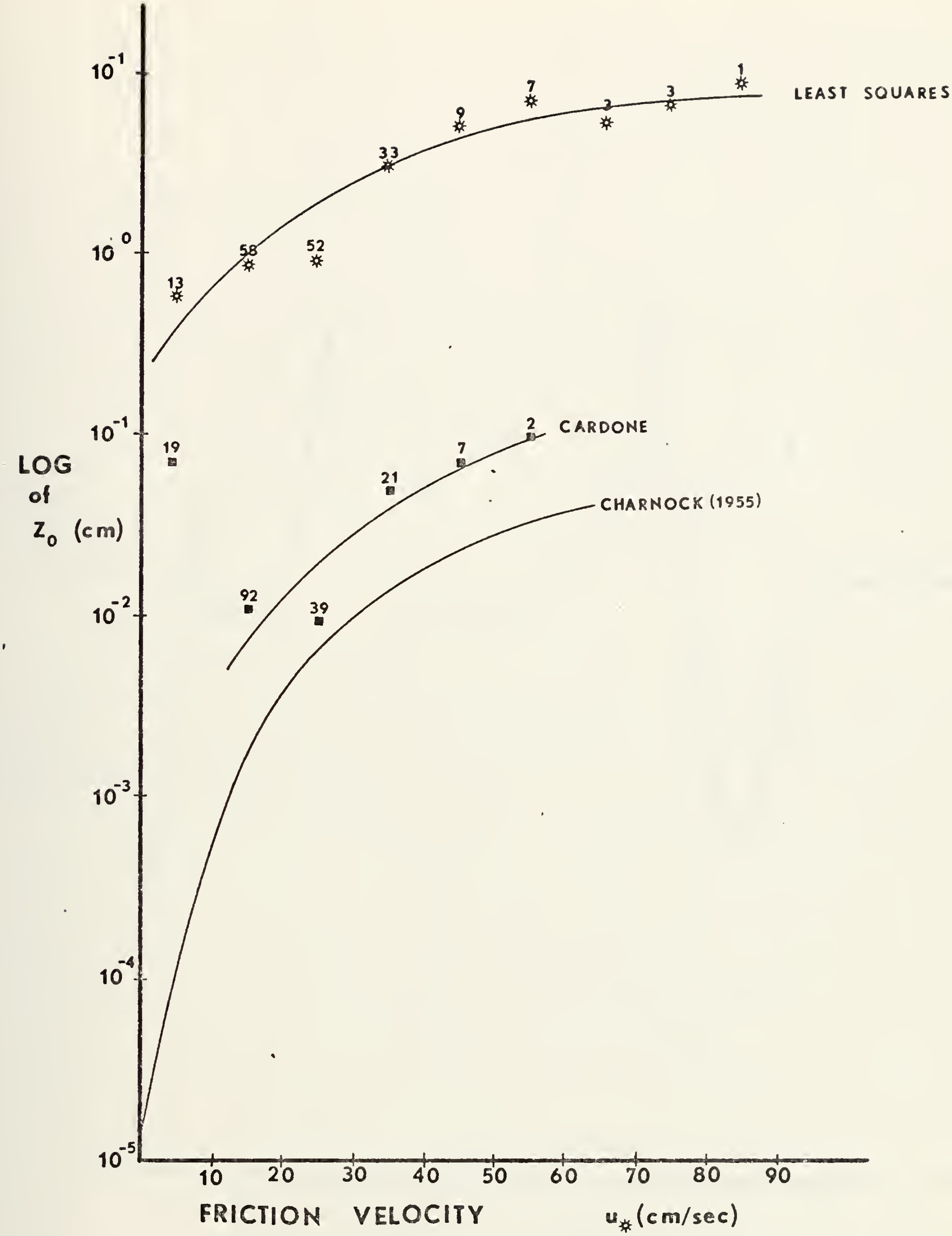
The results from the two methods are compared in figure 7 which is a logarithmic plot of z_o versus u_*. Comparison is also made with Charnock's (1955) expression.

$$z_o = \frac{u_*^2}{\alpha \; g} \qquad \alpha = 81.1 \tag{24}$$

The similar curvature of all three plots indicates agreement on the shape of the friction velocity and roughness length relationship. However, the least squares method produced roughness lengths on the order of one magnitude larger than Cardone's values.

In general, both methods appear to give good results, however, the average values obtained by the least squares method show less dispersion at low friction velocities than does Cardone's one level method.

A comparison of the roughness length versus the ten meter mean wind speed was made between results obtained by Ruggles (1970) and the least squares method as shown in figure 8. Ruggles hypothesised that the z_o peaks were associated with the effects of wind wave coupling. He designated the first peak as being coincident with the



LEAST SQUARES
CARDONE
CHARNOCK (1955)
LOG of Z_0 (cm)
FRICTION VELOCITY u_*(cm/sec)

Figure 7

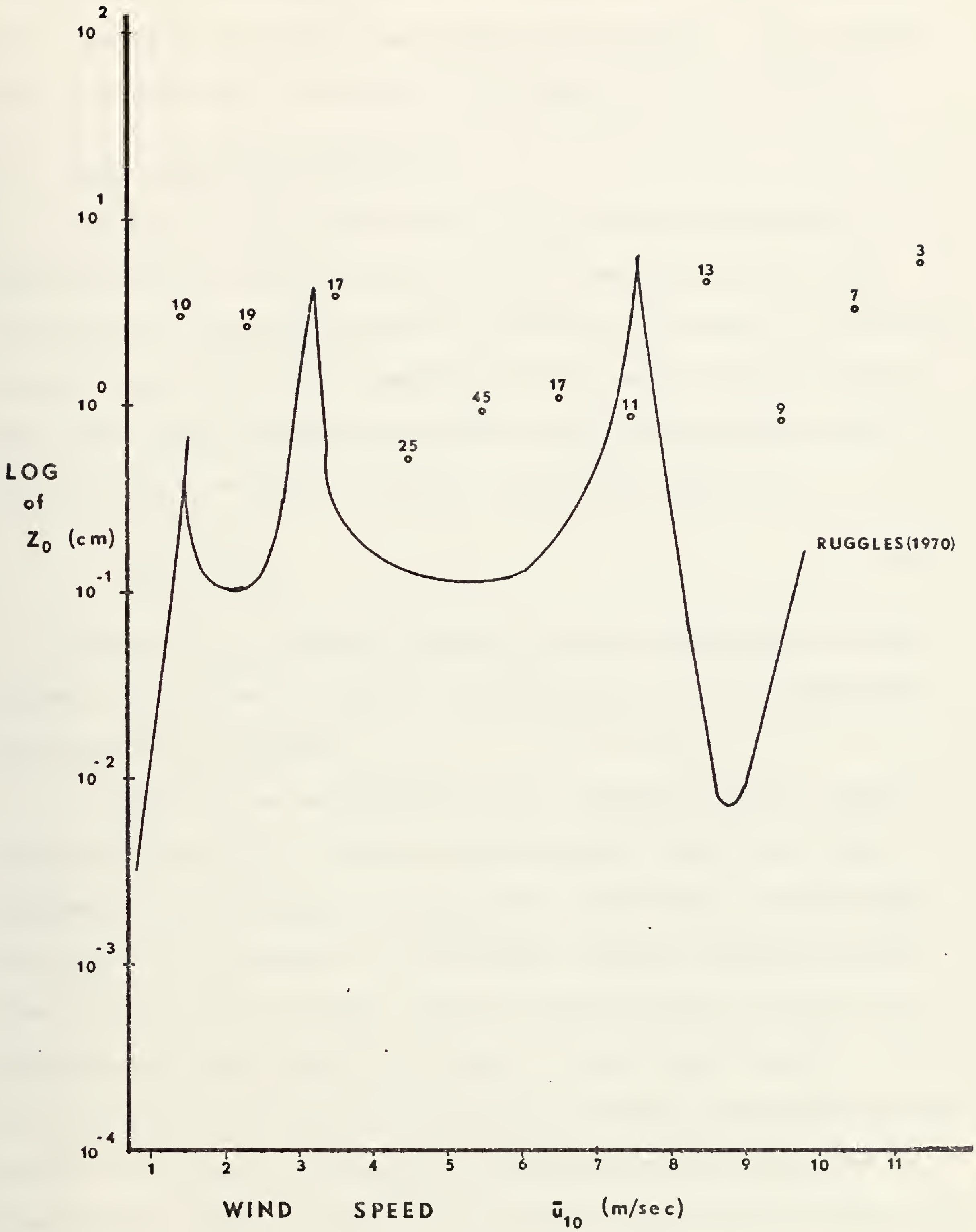

10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
LOG of Z0 (cm)
RUGGLES(1970)
10
19
17
25
45
17
11
13
9
7
3
1 2 3 4 5 6 7 8 9 10 11
WIND SPEED ū10 (m/sec)

Figure 8

minimum wind necessary for wave generation. The results of this study show similar maximums and minimums, most notibly the maximum near 3.5 meters and minimum near 4.5 meters.

B. DRAG COEFFICIENT RESULTS

Ten meter drag coefficients (C_{10}) were calculated to provide further verification of the compatibility of the experimental profile results to results of others. Friction velocities which were computed by the least squares method and also using Cardone's expression and the ten meter mean wind ($\overline{u}_{10}$) were used to obtain C_{10} by the expression

$$C_{10} = \frac{u_*^2}{\overline{u}_{10}{}^2} \tag{25}$$

Plots of C_{10} versus u_* and C_{10} versus Richardson number appear in figures 9 and 10. Superimposed on the graphs are the results of others.

In general, some aspects of the results compare favorably with results of others and indicate that over ocean shipboard application of turbulence similarity theory might be valid and feasible in the marine surface boundary layer. The least squares method produced average drag coefficients that were higher than the values of other experiments. This is attributed to the high values of friction velocity possibly due to the ship's influence. The problem was addressed by Cavanaugh (1974), however, his results were not as pronounced as those in this study.

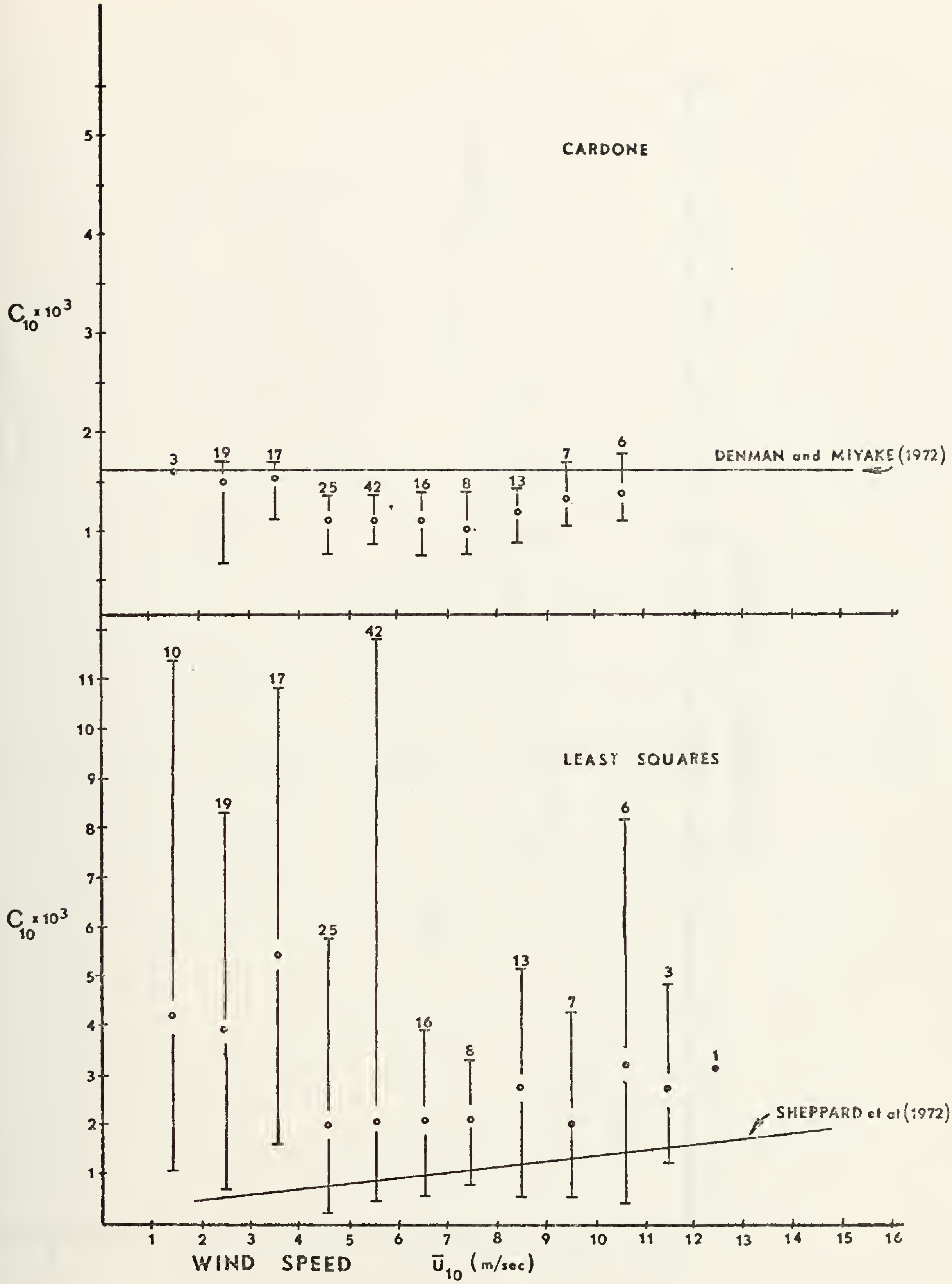
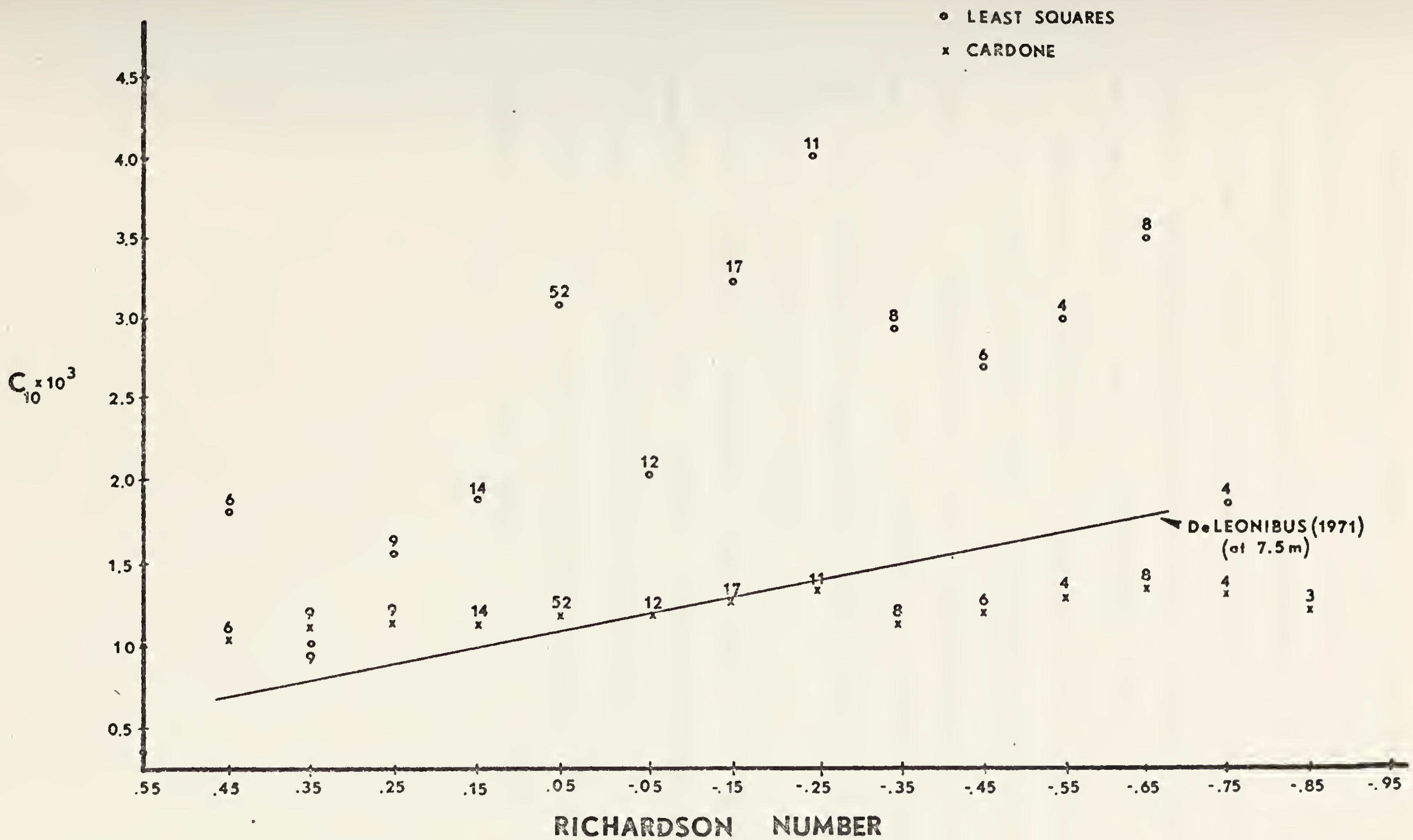

CARDONE
$C_{10} \times 10^3$
DENMAN and MIYAKE (1972)
LEAST SQUARES
$C_{10} \times 10^3$
SHEPPARD et al (1972)
WIND SPEED $\bar{U}_{10}$ (m/sec)

Figure 9



LEAST SQUARES
CARDONE
$C_{10} \times 10^3$
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
.55
.45
.35
.25
.15
.05
-.05
-.15
-.25
-.35
-.45
-.55
-.65
-.75
-.85
-.95
RICHARDSON NUMBER
DeLEONIBUS (1971)
(at 7.5 m)

Figure 10

C. TEMPERATURE STRUCTURE PARAMETER

The most important element for parameterizing optical propagation conditions in the marine surface boundary layer is the temperature structure parameter (C_T^2). The indirect method was adopted to define C_T^2 at the four instrument levels where a computed Richardson number was available. First, it was necessary to use the Richardson numbers to define the f_3 function in equation 17 that had been empirically derived from the Kansas field data. Equation 17 was then used to obtain C_T^2. Subsequently, the temperature structure parameter was transformed into the refractive index structure parameter, C_n^2 for additional comparisons with theoretical predictions, spectral and optical results.

Calculated C_T^2 decrease with height as expected for all stability conditions. Above a Richardson number of .20, the f_3 function in equation 17 is undefined.

Temperature structure parameter (C_T^2) results were compared to direct measurement values by Lund (1975).

VI. CONCLUSIONS AND RECOMMENDATIONS

The ship's motion and structure appeared to have had an effect on the wind profiles. This conclusion is based on the fact that the values of z_o and C_{10} obtained by a least squares fit profile data were consistently higher than values observed in other experiments.

Cavanaugh (1974) observed similar results and alluded to ship's motion influence on a logarithmic profile. Hull interference could disrupt the wind stream passing the instruments. This obstruction could cause the lower wind cups to slow and thus increase the apparent gradient. This would result in higher z_o values. This possible influence was examined in the analysis by disregarding the lower sensor level in the regression calculations. Roughness lengths were lowered slightly in most profiles examined, however, not enough to justify dropping this level in profile analyses.

A suggestion for future experiments would be to position a sonic anemometer vertically over the side of the hull at main deck level to measure the forced vertical air motion caused by hull wind blockage. From data obtained in this manner, a ships wind stream signature for varying wind speeds might be found. This could find application in the more complex study of measuring turbulent motion while underway.

With regard to temperature structure parameter estimates, the function f_3 is required. Sufficient data is now becoming

available to permit evaluation of equation 17 for over the ocean observations. Comparison of the C_T^2 spectral results obtained by Lund (1975) and those computed in this study could accomplish part of this task.

Because of the quantity of data to be screened only a cursory analysis of the observations has been completed in this study. More detailed examinations into the measurements would certainly yield additional knowledge, particularly with regard to the ship's motion and structure influences and instrument biases.

It would be desirable to have mean wind observations closer to the ocean surface. Combined with the present profiles, a more detailed description of wind-wave coupling and its effect on turbulent flow could be undertaken. The additional measurements could be made from a buoy positioned upwind of the ship. Another recommendation which is unrelated to application of turbulence similarity theory is that a small portable computer be obtained for future experiments to facilitate real time data analysis. The system now employed is extremely inefficient because many data discrepancies are not recognized until after the cruise.

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